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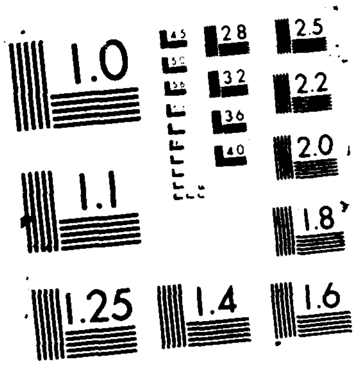
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Naval Research Laboratory
Washington, DC 20375-5000

NRL Memorandum Report 6084

Holography of the Ionosphere at HIPAS

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Interferometrics Inc.
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October 5, 1987

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The authors were tasked to investigate the Ionospheric Holography Experimental System undergoing development under UCLA auspices at HIPAS, including both questions of engineering feasibility and of the validity of interpretation of the results in terms of extracting meaningful information about the ionosphere. The conclusions in this report represent interactions with the UCLA group through approximately mid-September 1986.

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CONTENTS

Holography of the Ionosphere at HIPAS

Background:

The authors were tasked to investigate the Ionospheric Holography Experimental System undergoing development under UCLA auspices at HIPAS, including both questions of engineering feasibility and of the validity of interpretation of the results in terms of extracting meaningful information about the ionosphere. The conclusions in this report represent interactions with the UCLA group through approximately mid-September 1986.

General Remarks:

The authors were tasked to investigate the use of holographic techniques because of their background in radio astronomical interferometry. It should be borne in mind that in the radio astronomical context aperture synthesis imaging (ASI), defined as the phase differencing of several subapertures separated spatially, is a proven technique. It has been used with antennas separated by the diameter of the earth, and to make maps of astronomical objects with a dynamic range of greater than 30 decibels with a resolution of 250000+ pixels. True phase-coherent connection has been made of antennas separated by 100+ kilometers at an operating frequency of several gigahertz, and by VLBI methods at much greater distances. Thus, the basic validity of ASI is not in question. In present context, there are two questions to be answered; first, to what extent is this technique appropriate for analyzing reflections from the ionosphere? Second, is the experimental planning and budget adequate to accomplish the desired data-gathering objective?

Theoretical Considerations Affecting Ionospheric Holography

Radio astronomy aperture synthesis is, in fact, a type of holography with a locally-generated reference beam. The maps produced of the brightness distribution of the radio sources depend for their accuracy on the assumption that the radiation originates from <u>independent emitters or scatterers.</u> This corresponds to the diffuse case of holograms. An undisturbed ionosphere can be expected to act to first order like a <u>specular reflector</u> or mirror. Aperture synthesis methods will not produce an image of a specular reflecting layer, but rather an image of the transmitter. Only a thoroughly rough ionosphere will produce an image of the reflecting layer. The most important advantage of the aperture synthesis method is that it provides information on the radiation from a number of pixels that is much larger than the number of subapertures used. In order for this to be true, the signal from each emitter must be received at all subapertures (diffuse reflection). For specular reflection, the signal from each point is received at only one subaperture, ray optics applies, and the aperture synthesis technique has no relevance. The experimental situation of interest for the HIPAS ionosphere is likely to be an in-between case, perhaps best approximated by perturbations from a specular model. In this case, even if the entire sampling aperture were filled with probes each half-wavelength, a unique solution still would not be provided, as when irregularities developed each subaperture would no longer be a probe of a particular place on the sky. The solution to this conundrum lies in developing a series of models to indicate the experimental effects of various perturbations of the ionosphere. It should be noted that this process does not invalidate the concept of using holographic techniques to investigate the ionosphere. It simply means that interpretation of experimental results requires a physicist's judgement. It is important to note that for any type of holography, an image of the object can only be produced if diffuse reflection/emission is the dominant mechanism.

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First, let us ask what would happen if the height of a specular reflecting layer were to move up, without irregularities developing. (This might correspond to the most important effect of a caviton developing). For this perturbation, the received phase at all antennas would change by an amount equal to 2 X the height change (times a secant factor). One could in principle, detect this effect with a single antenna. Note in particular that the 300 meter Z-direction resolution limit predicted by aperture synthesis does not apply here, because resolution of independent diffuse emitters is not being attempted. In this situation, reflecting height changes of much less than one-half wavelength can be measured. An obvious extension of this line of thought indicates that in order to detect a plane tilt plus height change only requires five antennas.

The next interesting case to consider is what happens if the ionosphere develops irregularities as a result of heating (or any other cause). The theory here should be reasonably similar to scintillation theory. Three cases can be distinguished; either the perturbations are less than 1/2 wavelength in size, approximately equal to that size, or greater. Irregularities much less than 1/2 wavelength, or 30 meters, in size will not affect the signal. Irregularities of approximately 1/2 wavelength or greater in size will result in scattering over an angle dh/dl, where dh/dl is the effective ionospheric height gradient caused by a local change in the electron content. For disturbances of a particular size, the effect on a receiver array will depend on whether the distance to the ionosphere is greater or less than the Fresnel zone size. If it is less, a random distribution of phase changes can be expected. If more, non-random, patchy changes can be expected.

Another way to think of this is as follows. For a specular ionosphere, the array of receivers will image the transmitter beam. Irregularities in the ionosphere will cause the beam image to "fuzz", with a size equal to the ionospheric height gradient for small disturbances, and with a "patchy" appearance for disturbances greater than the Fresnel zone size.

In sum, the expected number of 20-30 receivers is almost certainly adequate to tell most interesting things that will happen to the ionosphere during a heating event. Neither the theory of diffuse reflection (DR) nor the theory of specular reflection (SR) can be expected to apply exactly, which will mean that there will need to be some modeling and intelligent analysis in any event in order to understand the changes.

For diffuse reflection, a meaningful vertical resolution can be attained only if the ionosphere is in the near field of the array. Figure 1A illustrates the near field limit as a function of aperture size, using the accepted formula. Figure 1C indicates the expected vertical resolution for diffuse reflection. (Note that this limit does not apply for specular reflection.)

Another important point to understand is the horizontal resolution attainable with a holographic system. Figure 1B shows the geometry for horizontal resolution with a holographic system. The most sensitive resolution possible is with a system with a baseline that is extended by an amount close to the distance to the ionospheric reflecting layer. Under these conditions, a horizontal resolution of less than one-half the operating wavelength, or 15 meters, is possible. Shorter baselines result in poorer horizontal resolution. This has been a bearing on the detectable size of caviton or other disturbance. For the current 207 meter diameter circle, the resolution is much poorer than 15 meters, about 1 kilometer.

There are two non-linear image techniques used in radio astronomy aperture synthesis image processing that may be of significant help in analyzing ionospheric data. The first of these is "SELF-CAL"; this is an algorithm for automatically adjusting phase and amplitude for individual receivers to optimize

the beam p n on a point source. If an unperturbed ionospheric reflection can be idei. ed, this technique should provide an excellent methods for calib rating thc ivers. (Whether this can he done requires experimental experience.) The other important technique is "CLEAN", in which an iterative subtraction of grating sidelobes is used to improve the dynamic range of an image. The CLEAN technique has recently been extended by Tsao and Steinberg with applications to specular targets.

Additional complications mentioned by members of the ionospheric committee include the possibility of irregularities in the path introducing non-uniformity in the up-down path at various azimuths, whether full-wave integration of the reflection process is necessary, and ordinary versus extraordinary propagation. It is our opinion that the first two effects in practice do not invalidate the holographic technique, and can essentially be treated as perturbations under normal conditions. The full-wave condition amounts essentially to realizing that the transmitted wave undergoes reflection in a finite curve rather than by ray geometry. This can be taken care of to first order by using an effective height of reflection in holography studies; UCLA now has full-wave integration techniques available. The "wiggles" problem is not as severe as might be thought because under most ionospheric conditions significant interaction between a wave of a specific frequency below the critical frequency and the electron gas takes place within a small range of heights because of the large gradient in the ionosphere electron density profile. Under these conditions the "wiggly effect" is subsumed in the other analysis of the image.

An additional topic of interest to the development of this technique is the fact that it is possible, by using different frequencies to probe different layers in the ionosphere. Thus, it may be possible to probe the surface just below and above a caviton or other irregularity and obtain sensitive information on its geometry.

A limited amount of work has been done in holographic-type investigations of the ionosphere. Several papers have been published, both by a Dutch group and by S.H. Knowles, in which the properties of the ionosphere were investigated by looking at perturbations in phase of the transmitted signal through the ionosphere from a natural radio source. Earlier, a study interpreted in terms of holographic qualities of a satellite signal was performed by Schmidt, Oksman, and Tauriainen. Schmidt et al. made experimental observations in Finland of ionospheric scatterers using VHF (150 MHz) signals transmitted by a satellite. They made two-dimensional (X-Z) holograms. They found the presence of one to several isolated scatterers. These studies may not have much relevance to HIPAS because of the difference in wavelength. The Fresnel zone for the ionospheric heights and observing wavelength used at HIPAS is of the order of several kilometers. This amounts to saying that we are dealing with a near field or undeveloped scintillation case, and it is not clear that diffuse reflection theory is relevant. Stone and Hildebrand also proposed a radio camera technique, but never published experimental results. They suggested using a number of antennas to obtain a three-dimensional transform. They were also discussing VHF irregularities. The typical Fresnel zone size at 150 MHz is about 500 meters. The above studies all consider the behavior of the ionosphere at frequencies well above critical, and are of only limited relevance to reflection holography at frequencies below critical. A limited amount of more relevant work has been done using the ionospheric heating facility previously located in Colorado, later transferred to Fairbanks. This work used a separate probing radar that utilized a ring of 32 antennas located in a circle with a diameter of 600 meters. The radar had resolution in both range and doppler. In operation, the vector sum was computed at a variety of positions, and the maximum was used to determine the tilt of the local ionosphere at a particular

doppler shift (Allen et. al.). The loci for a number of doppler shifts were then combined to form a "total power sky map". Although this did not correspond to a complete holographic analysis, the results did demonstrate that in the mid-latitude regions the suggestion that a quasi-specular model is normally appropriate under unheated conditions was verified. On the other hand, the Platteville experimenters did find that under heated conditions the return broke up into doppler and range ("spread-F"). It is recommended that, failing anything better, this work be used as a basis for a model of the arctic non-auroral ionosphere to be tested against observations. The Colorado group used a ray-tracing program to analyze returns. Observations were also made of typical behavior at UHF from this heater. Similar work has been performed recently using the Tromso, Norway heating facility. Other ionospheric experiments have used interferometers to measure direction of travel of waves, etc., without any detailed analysis of the distribution. A limited amount of work has also been performed using holography to define objects under ground (Osumi and Ueno) and under ice (Yen). This work is of interest because it demonstrates the validity of holographic techniques through a varying dielectric medium.

Experimental Investigations and Simulations

Our group performed several simulations using the AIPS (Astronomical Image Processing Software) system that are relevant to the HIPAS experiment. This software system is designed to process two-dimensional image information primarily from aperture synthesis radio astronomy instruments including short and long baseline interferometers. In connection with other work, we had previously extended this package to handle three dimensional cases. Our first simulation was a computation of the predicted synthesized beam pattern for a configuration of 30 antennas laid out at approximately equal intervals along the Chena Hot Springs Road into Fairbanks, and back out to Eielson A.F.B. along the Richardson Highway. This corresponded to the approximate configuration that at the time was intended to be implemented in the summer of 1986, with installation at private dwellings (Table I). The figure of 30 was somewhat arbitrarily set as the maximum conveniently usable by the AIPS software. The resulting beam patterns are shown in Figure 2 for both the X-Y (horizontal) plane and X-Z (vertical) plane. <u>It is important to note that the theoretical questions mentioned above concerning the interpretation of observed holograms do not apply to the computation of antenna patterns, which is always relevant</u>. We include, for both planes, contour plots of the antenna patterns and one dimensional beam slices that give a more quantitative idea of the beam quality. Both sets of graphs are for a target height of 300 km. Also included is a set of spatial frequency plots in both the horizontal and vertical planes; these give an indication of the extent to which a filled aperture is simulated.

For this configuration, the beam quality in the horizontal plane is excellent, with no grating lobes above 10%. As a matter of fact, it is so good that a configuration with fewer antennas would probably give adequate results. The computed horizontal resolution (DR) is about 60 meters. In the Z-plane, the resolution is a factor of 5 poorer, giving about 300 meters resolution (DR). As expected, the Z-direction resolution is better for a lower ionospheric height, and poorer for a higher ionospheric height.

In addition to the above-mentioned analysis of the patterns resulting from a distribution of antennas over the HIPAS - Fairbanks Road, additional work was performed on the 207 meter diameter circle of receivers that was put in place by UCLA in Spring 1986. First, the beam patterns were computed. Second, some examples of recorded amplitudes and phases from HIPAS were used to independently compute the resulting pattern in the X-Y plane (the depth plane was not

computed, because there is not significant Z-direction resolution with this array). An attempt was first made to do this using AIPS, and satisfactory results were not obtained. The reason for this is not completely understood. Rather than attempting to understand what went on in the depths of the AIPS software system, we chose to write our own routine for making vector combination. Contour maps were produced to compare with those produced at UCLA. As Figures 3A - 3G show, the agreement was generally satisfactory. It is difficult to make exact comparisons of contour maps, especially when the contour normalization used in the UCLA maps was different from ours. NRL did not include some refinements used in the UCLA model, such as inclusion of the dipole pattern. Figure 3 includes results when a "CLEAN" solution was experimentally performed on some of the patterns. This was done as an experiment, and interpretation of the results is uncertain. Data samples included both reasonably disturbed and reasonably quiet conditions (see Figure captions). The CLEAN technique seemed to provide a series of sources that was more complex for a disturbed ionosphere. Its further experimental use for HIPAS data is recommended. One conclusion from the analysis of the patterns is that it is difficult to observe fine details of the ionospheric reflection structure, since the sidelobe level is quite high. This can be remedied by the inclusion of more antennas. A more extensive data base is also needed in order to characterize the conditions normally expected.

Engineering Considerations:

In this section will be included practical considerations of receiver design and a deployment plan. As stated in the introduction, there is no doubt that a functioning holography system can be built, since far more taxing phase stability requirements have been satisfied over similar distances. The items in question are whether the budget is adequate for the experimental configuration, and whether all portions of the design are properly conceived and executed.

General:

The budget appeared to be very inadequate for the deployment of an effective holographic system. Some of this can, no doubt, be overcome by use of "cheap" graduate students and by ingenious design. However, the use of continual optimism to replace a real commitment of resources can only go so far. one particular consequence of this financial pressure is a continual changing of objectives to the point where it is difficult to make a mature judgment of what is being achieved in comparison to what was intended. Although estimates of the cost of establishing remote receiver sites can vary significantly depending on the details of the design, a figure of $25K per remote site seems a reasonable minimum. The present budget allows far less than this. It should be further noted that there seems to be a lack of continuity on the working level at UCLA. Although some changes in personnel are inevitable in a school environment, this does not help the project progress. The proposed hiring of a senior-level radio scientist to take responsibility for experimental design and construction would certainly be a welcome step. It would also seem that a much more active collaboration with locally-based University of Alaska Geophysical Institute would be beneficial.

The individual receiver design seems now to be well under control. Although there was some initial confusion about what is necessary in the way of phase referencing, the receiver design now appears to be satisfactory; the lab oratory calibration procedure both for amplitude and phase appears to function well. The initial "holograms" seem to be encouraging, in that they seem to be

reasonably representative of what is to be expected of an only moderately perturbed ionosphere. One problem seems to be that it is difficult to obtain a "control" pattern that represents a known situation to independently judge the accuracy of the amplitude and phase calibration of the receivers.

The present configuration consists of eight receivers with all relative phase referencing accomplished by cable interconnection. Additional technical and practical problems remain to be solved in the deployment of a more extensive system. In particular, the method of phase referencing, siting, power supply and data collection for receivers separated by a distance great enough that direct cable interconnection is impossible, must be satisfactorily determined.

The question of the location and phase interconnection of the complete configuration of remote receivers remains to be resolved. To achieve maximum coverage of the u-v plane, the receiving nodes must be scattered over a baseline representing the reciprocal of the angular resolution to be achieved. The exact location of each receiver is unimportant, but a reasonably wide and uniform distribution is best to assure coverage of the spatial frequency plane. We were not satisfied that a realistic, cost-effective way to place these receivers had been achieved. Methods proposed have included placement in settlers' homes along the highway, perhaps with payment of a small consideration. We were not convinced that this scheme would work, although someone with high powers of persuasion could perhaps carry it out. A more realistic scheme would involve placing a limited number semi-permanently with portable generators. We did not see realistic costing for this. A suggested scheme was to form "clusters" of antennas (8 in each cluster) separated by a small enough distance (several hundred yards) to enable interconnection of antennas by means of cables, with electronics located in a central area such as a motor home. The problem with this is that it does not result in a good spreading out of the subapertures over the u-v plane, so that the additional receivers are not utilized effectively. We strongly discouraged UCLA from pursuing this approach for the reason given. The latest proposal involved placing receivers at the extreme corners of the UCLA-owned site for the next increment. This seems a useful thing to do, although still relatively far from the full planned deployment. Geometrically, the scheme of placing receivers along the road to Fairbanks and out generated a good distribution. Another example of a good distribution is the circular distribution used at Plattesville.

An important issue when using spaced receivers is how to maintain phase interstability. To maintain true phase stability to the level of 10 degrees of phase, a timing accuracy of the order of 5 nanoseconds is required. Contrary to the expectations of some ionospheric physicists, maintaining this stability over baselines of up to 50 kilometers is not a significant problem if adequate funding is available. Radio astronomy interferometers routinely maintain phase stability of the order of 5 picoseconds over distances of up to 100 kilometers by the use of closed-loop microwave links. In the microwave link system, compensation for path delay changes is made automatically by means of a closed-loop phase-measuring servo. This system can be expected to cost on the order of $30K per link. If this level of funding is not supportable, things become more difficult. Other possible methods that have been suggested include a conducting balloon reference (difficult in practice and hard to locate precisely y enough), and phase referencing via propagated ground wave at either the fundamental or the second harmonic (not enough signal propagated to distances beyond a few kilometers to detect properly; also it cannot be expected that the propagation velocity will remain constant to the desired accuracy.)

Probably the most practical idea is of using a television broadcast color subcarrier. (The following facts are paraphrased from NBS Pub. 557.) The major television networks use atomic oscillators, either cesium or rubidium, to

generate their reference signals. Thus, all broadcast frequency references have an accuracy of a few parts in 10^{12}. All color broadcasts have a color subcarrier with this precision at a frequency of 3.579545454...MHz., generated by taking a ratio 63/88 times a 5 MHz reference from a frequency standard. All color television receivers have a circuit that phase-locks to this subcarrier to generate the color signals used for the picture. Thus, minor modifications to a $150 standard color television receiver produce a signal that is directly linked to an accurate phase reference. The phase-linking is inherently precise because in the NTSC scheme accurate color fidelity depends on accurate color subcarrier phase. For use with a holography system HIPAS the receiver local phases will all be compared to a single phase transmitted from a local Fairbanks television station. Apparently enough signal is propagated from Fairbanks to the HIPAS area to give an acceptable signal level. (This was not independently checked).

The relevant question is then what phase stability can be expected over the path from the transmitter to the several receivers. Limited information about the expected accuracy can be obtained from NBS pub. 557 (p. 138). They quote estimated accuracy for oscillator frequency determination for various measurement time intervals. These numbers can be converted from fractional frequency units to accumulated time errors, and thus phase errors, by simply multiplying by the time interval. Relevant numbers are 3 nanoseconds error for a time interval of 10 seconds, and 27 nanoseconds error for an interval of 30 minutes. The latter number corresponds to about 30 degrees of phase at the frequency of interest.

Several comments should be made about this number. First, the phase error as a function of time may be expected to have bounded growth as a function of delta time, so that the estimated accumulated time error for a 24 hour interval would be somewhat greater than 27 nanoseconds, but not a great deal. Second, these error estimates are conservative, being designed as a worst-case estimate for a user-oriented system. The appropriate NBS representative stated in a telecon that those error limits were probably quite conservative and, more importantly, had not been extensively tested. The reason is that, when used for time transfer, these numbers approach the-state-of-the-art in frequency standards. In practice, the use of this system should be the subject of experiment. It should be noted that, although uncompensated phase errors of thirty degrees will cause problems in mapping, there exist techniques used by the radio astronomy community for calibrating these phase errors if a known reference source with small phase errors is available (see below). If this level of phase intercomparison can be achieved, then phase interstability of the receivers is easily attained <u>provided</u> that the receivers are designed properly. This is done by assuring that all local oscillators are derived by synthesis from the received frequency/phase reference.

A companion problem to maintaining phase stability between stations is the development of a phase calibration system to remove remaining errors, as well as to verify correct system operation. For radio astronomy interferometers, the calibration of the absolute value of the phase difference is conveniently made by means of observations of a radio source that is known to be of small diameter (a "point" source). The relative phase offsets of individual stations are then adjusted to maximize output by a process known as "SELF-CAL". The radio source method cannot be used by HIPAS because the collecting area of an individual subaperture is too small. An alternative is to observe the ionosphere under undisturbed conditions; the undisturbed ionosphere should provide an image of the transmitter beam. Unfortunately, such conditions may be relatively rare. A fairly large data base of ionospheric "snapshots" should be maintained and examined to see to what extent this technique is practical. Another technique

discussed involved monitoring reflections from a balloon floated over the transmitter. This was never demonstrated successfully, and would probably involve relatively large practical difficulties. It may be possible to operate successfully without a calibration system, although its inclusion is clearly desirable.

RECOMMENDATIONS: It seems clear to us, in spite of the doubts of other members of the ionospheric science community, that the holography technique is capable, when properly used, of providing significant information about the structure of the ionosphere, both under disturbed and undisturbed conditions. Proper use requires a thorough knowledge of holographic principles for both specular and non-specular reflection. Interpretation of the results cannot be approached in a simplistic manner. The physical background developed in scintillation theory is of significant help in understanding the physics of the situation. It is clearly possible to implement a technically adequate holographic array at a moderate cost. However, the cost and resource limitations on this project are so severe that they do not permit adequate planning.

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TABLE I

Positions of Antennas Used In HIPAS - Fairbanks - Eielson Beam Computation

E-W	N-S
-2784	161
-5760	209
-8882	-306
-11295	-611
-14513	-885
-19919	1207
-22719	1207
25615	772
28608	1689
-32180	1689
-35108	965
-37860	-106
-39903	- 805
-41448	-3145
-41721	-6002
-39292	-6887
-35961	-7385
-33725	-9010
-27981	-12003
-25100	-13033
-22832	-14835
-20306	-16798
-17490	-18021
-14626	-19549
-13580	-22542
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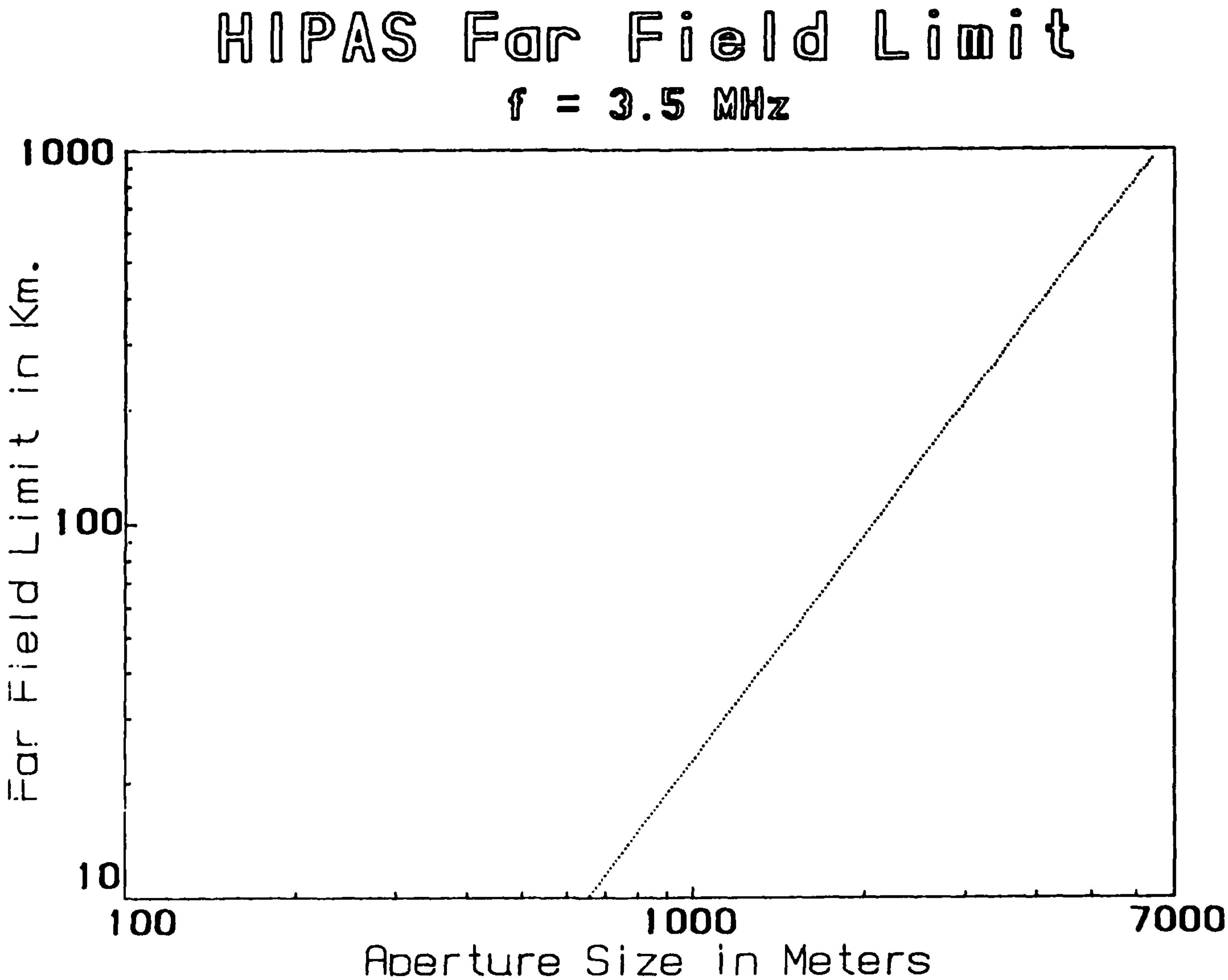

Figure 1 —A—HIPAS Far Field Limit—Far field limit in kilometers vs. maximum aperture size in meters. Depth resolution using holographic techniques is only possible for objects appreciably closer than the far-field limit.

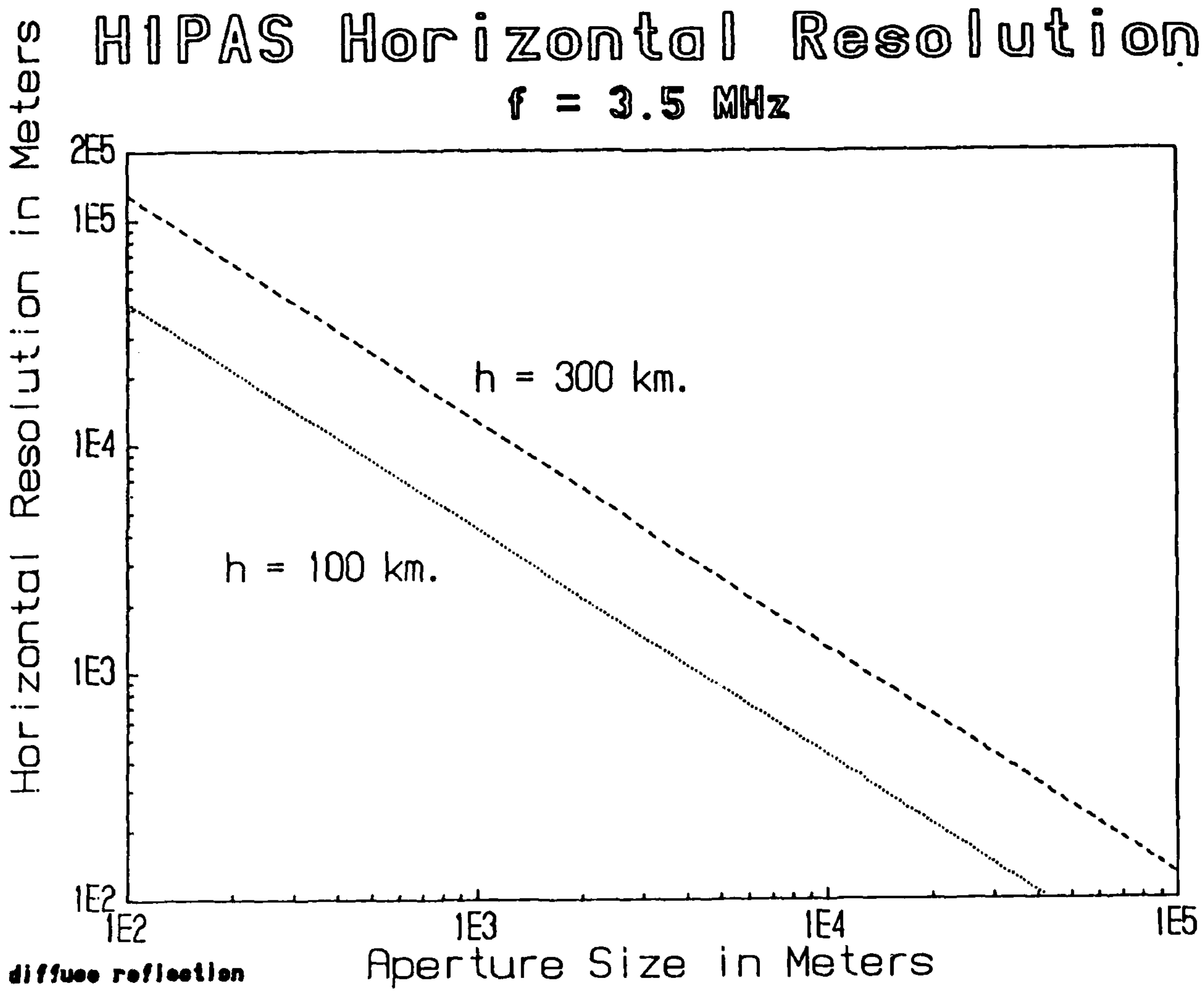

Figure 1 —B—Approximate horizontal resolution for ionospheric reflection as a function of maximum holography aperture. Nominal reflection heights of 100 km. and 300 km. have been plotted. These are intended to correspond loosely to auroral reflection and F-region reflection, respectively. A diffuse reflection mechanism has been assumed.

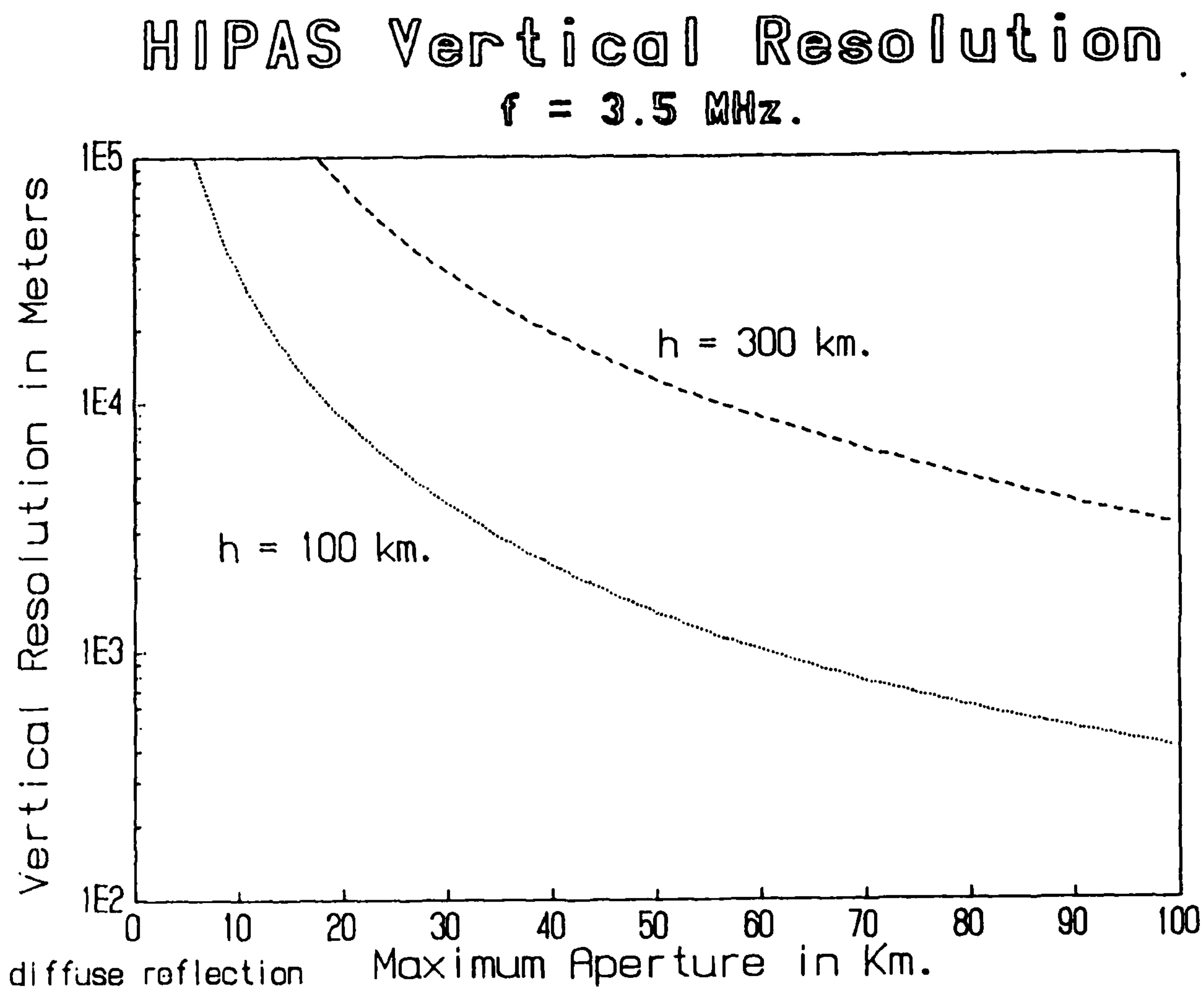

Figure 1 –C–Approximate holographic vertical resolution at various ionospheric reflection heights as a function of maximum aperture. Nominal reflection heights are the same as in Figure B. This figure is appropriate for diffuse reflection. For specular reflection the vertical resolution is better than 1/2 wavelength.

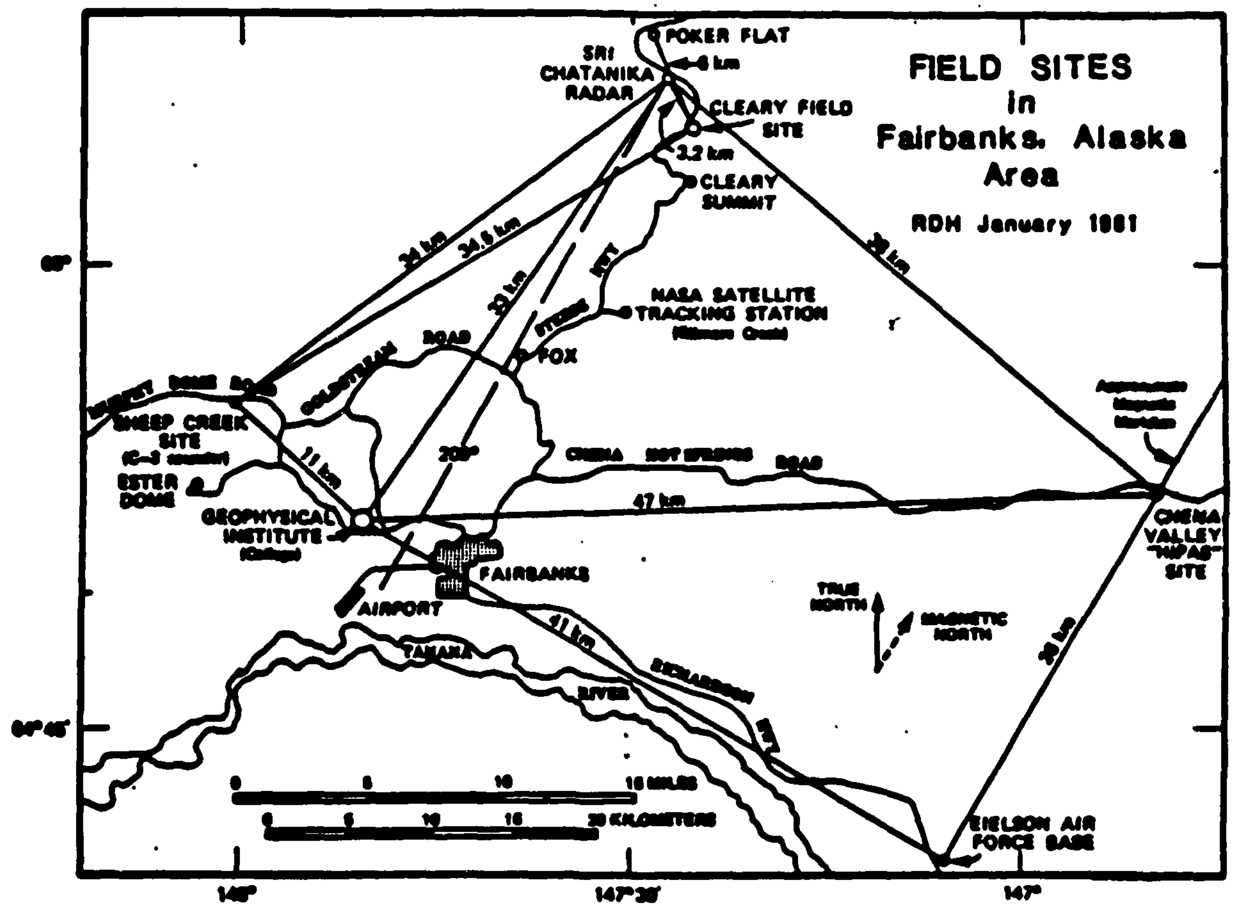

Figure 2.—Patterns for Chena-Fairbanks-Eielson baseline with 30 antennas

A—Map of local area

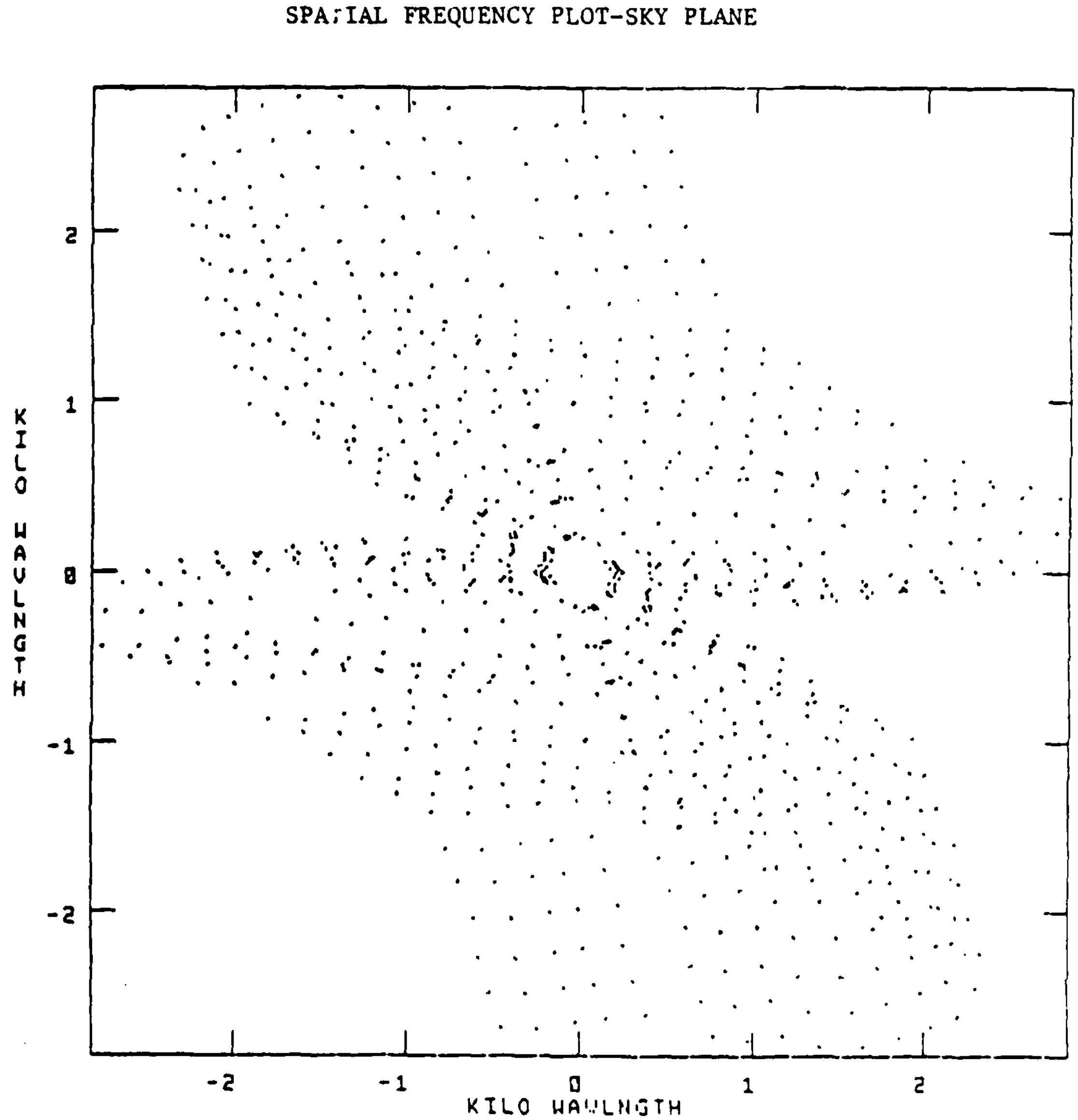

Figure 2 (Continued)—Patterns for Chena-Fairbanks-Eielson baseline with 30 antennas

B—Horizontal spatial frequency plot

Horizontal Pattern,
300 km Height

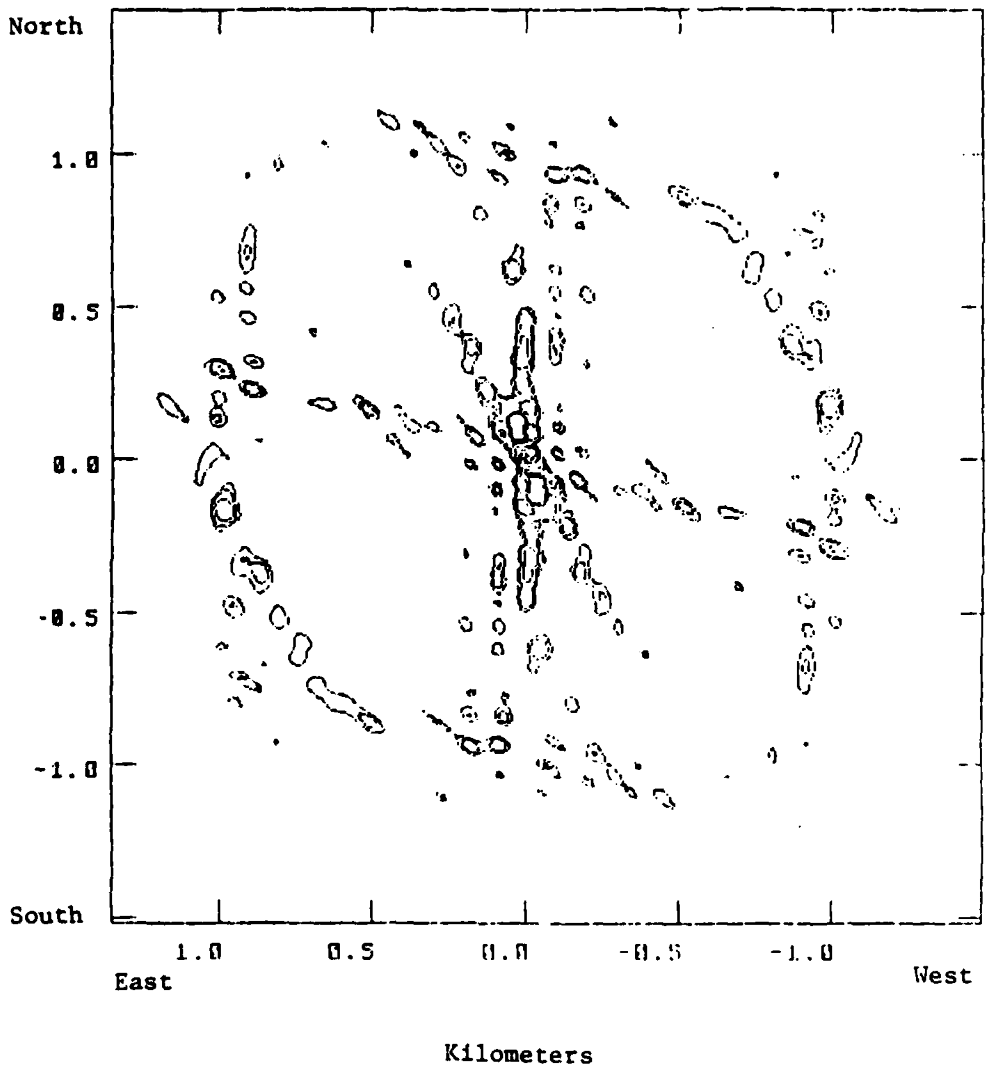

Figure 2 (Continued)—Patterns for Chena-Fairbanks-Eielson baseline with 30 antennas

C—Horizontal beam pattern

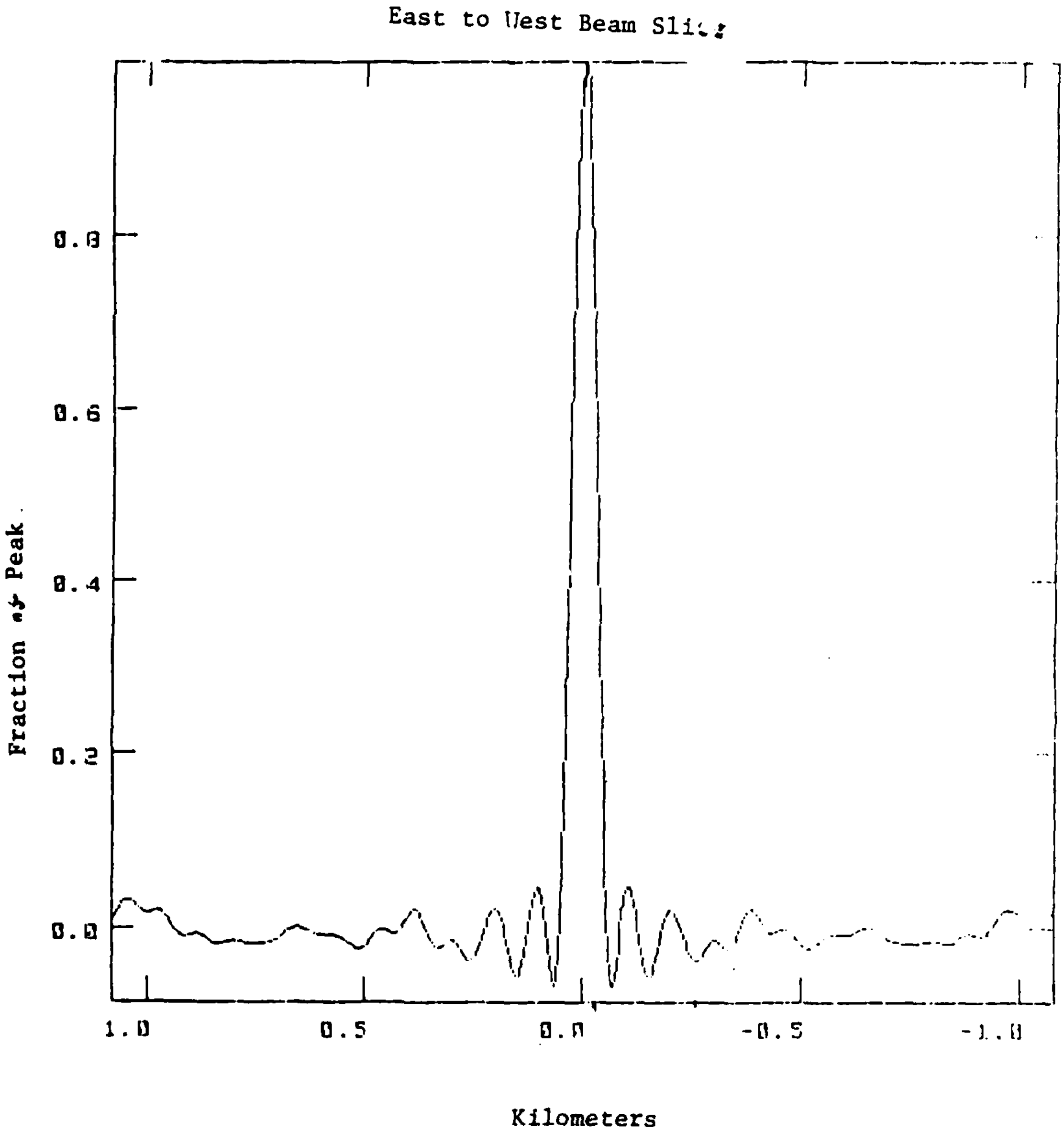

Figure 2 (Continued)—Patterns for Chena-Fairbanks-Eielson baseline with 30 antennas

D—Horizontal beam slice

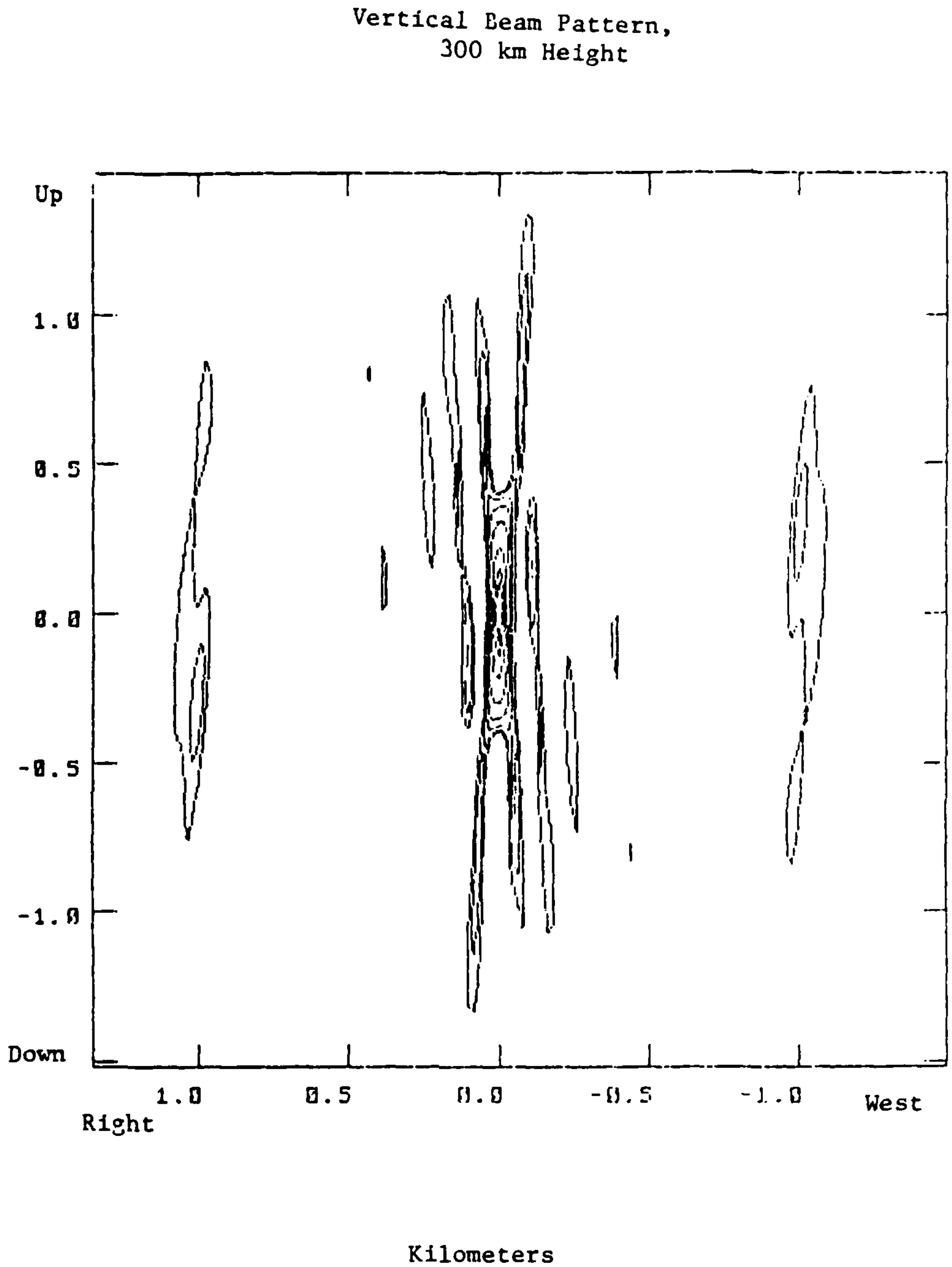

Figure 2 (Continued)—Patterns for Chena-Fairbanks-Eielson baseline with 30 antennas

E—Vertical beam pattern

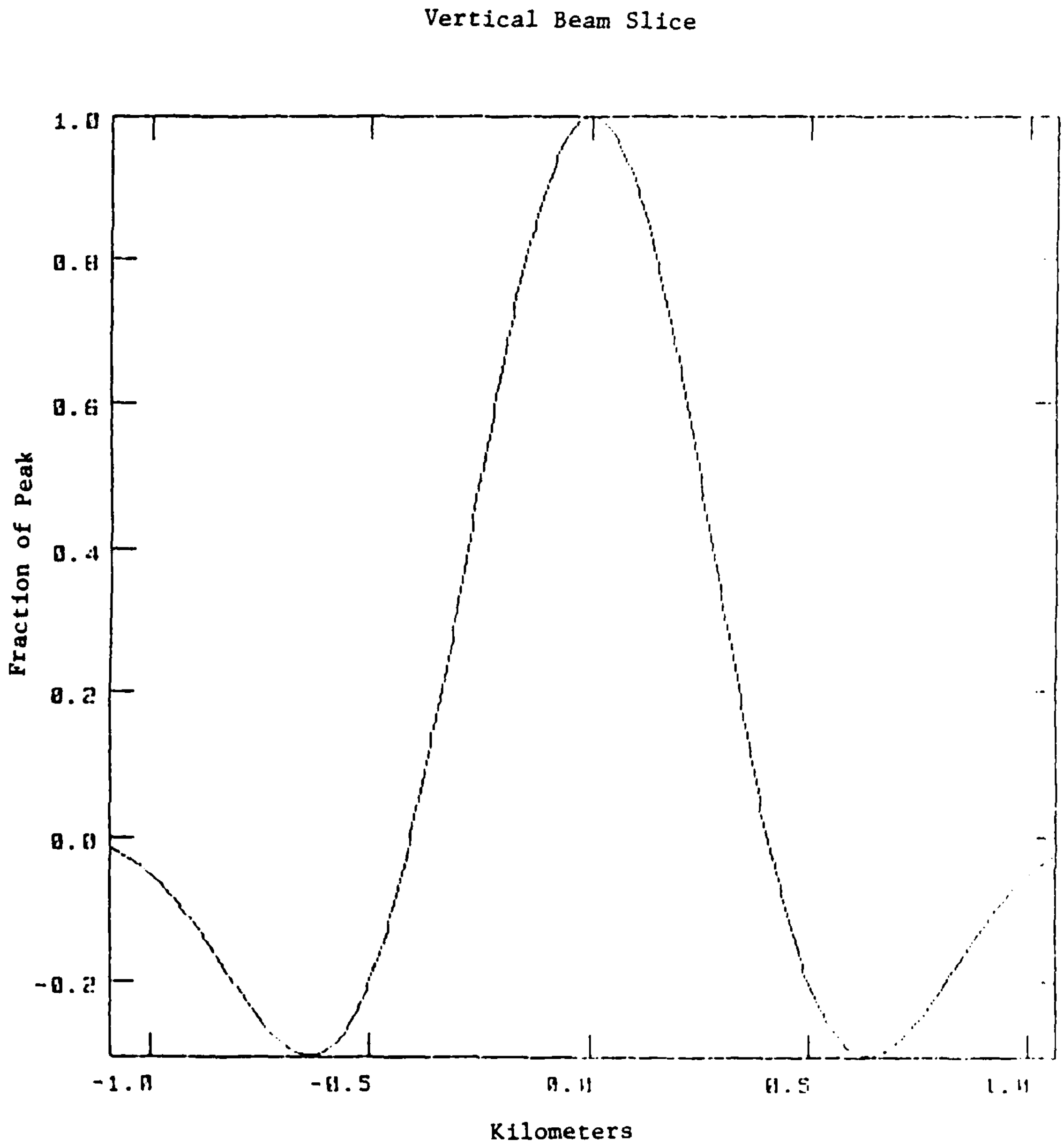

Figure 2 (Continued)—Patterns for Chena-Fairbanks-Eielson baseline with 30 antennas

F—Vertical beam slice

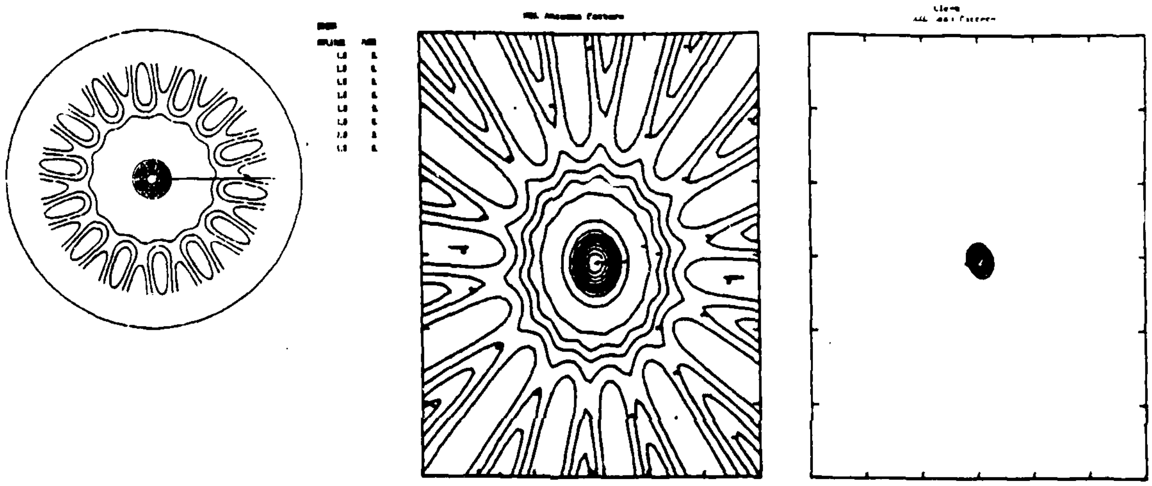

Figure 3 —A series of patterns dealing with the 206-meter 8-antenna configuration used at HIPAS during Spring-Summer 1986

A—Comparison of predicted horizontal plane beam pattern with that produced at UCLA. The UCLA pattern uses 10% interval markings, while the NRL version uses non-normalized intervals as indicated on the charts. The UCLA pattern has been rotated so that north is at the top of the page. Also included is the NRL aperture pattern CLEANed with an appropriate Gaussian beam.

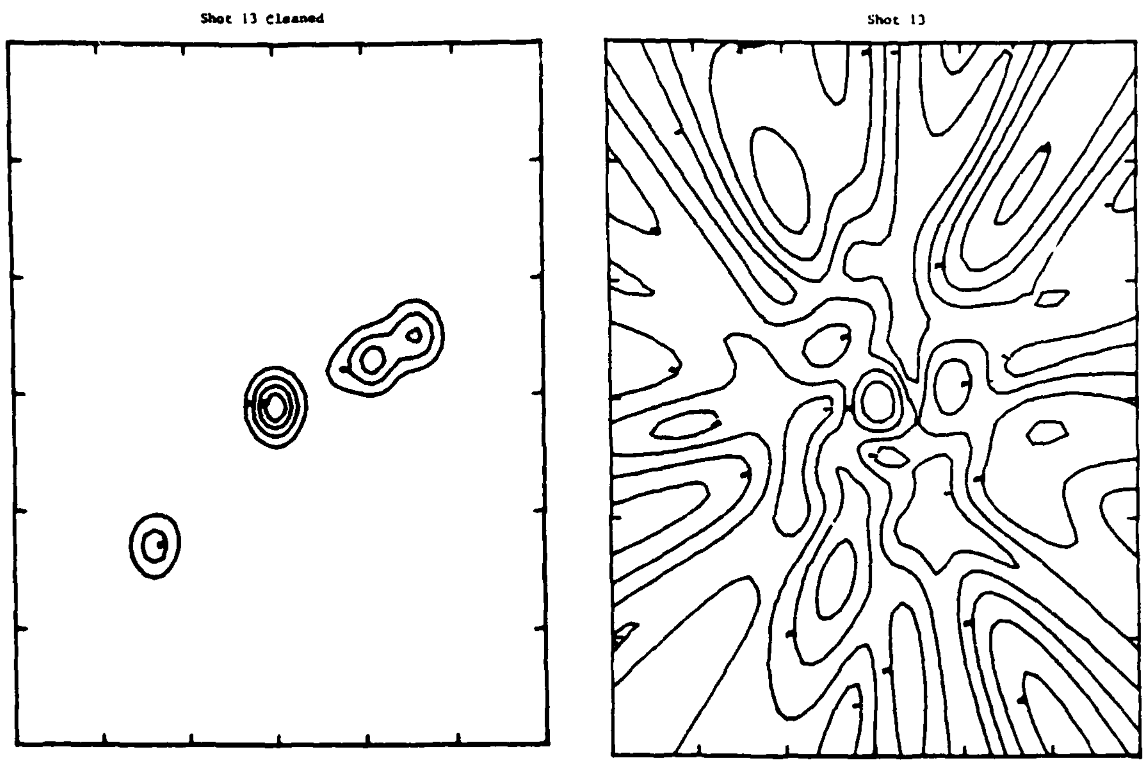

Figure 3 (Continued)—B, C, D, E, F, G—Holographic reconstructions (horizontal plane) for several "shots" during spring-summer 1986. 3B, C, D, represent shots 13, 14, and 15 of 5/13/86 during disturbed ionospheric conditions. CLEANed representations are also included. 3E, F, and G are shots 1, 2, and 3 taken at a later date under undisturbed conditions.

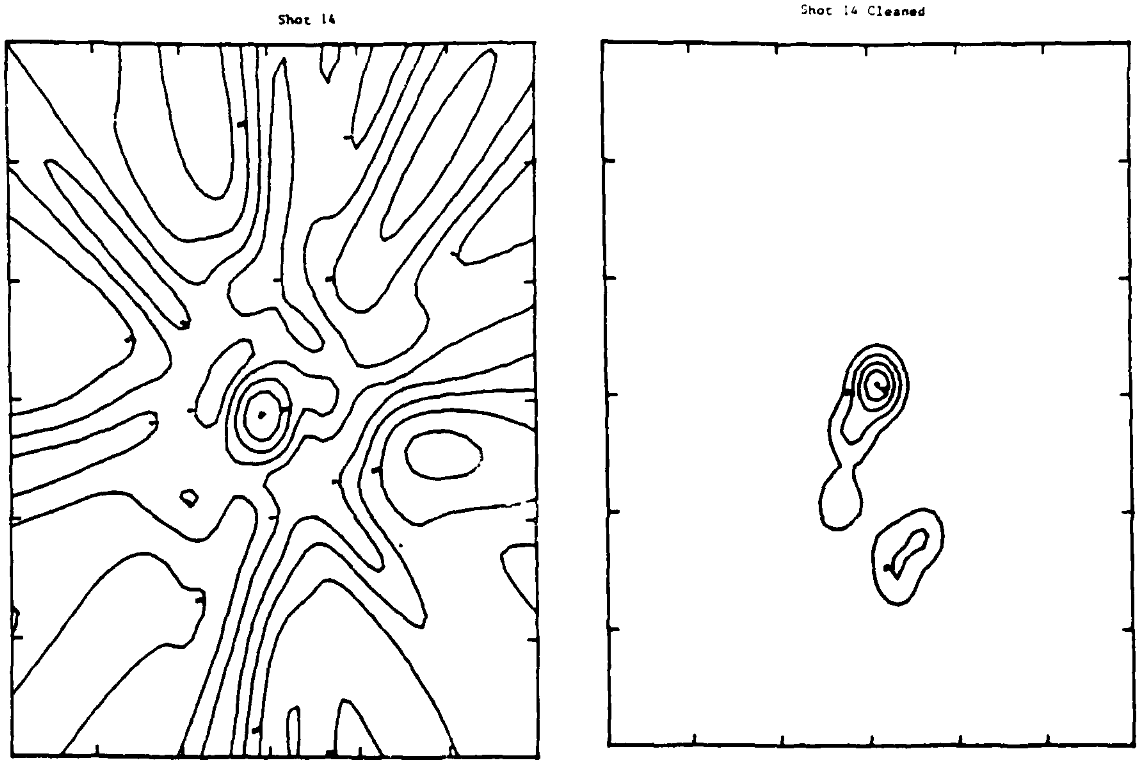

Figure 3 (Continued)—B, C, D, E, F, G—Holographic reconstructions (horizontal plane) for several "shots" during spring-summer 1986. 3B, C, D, represent shots 13, 14, and 15 of 5/13/86 during disturbed ionospheric conditions. CLEANed representations are also included. 3E, F, and G are shots 1, 2, and 3 taken at a later date under undisturbed conditions.

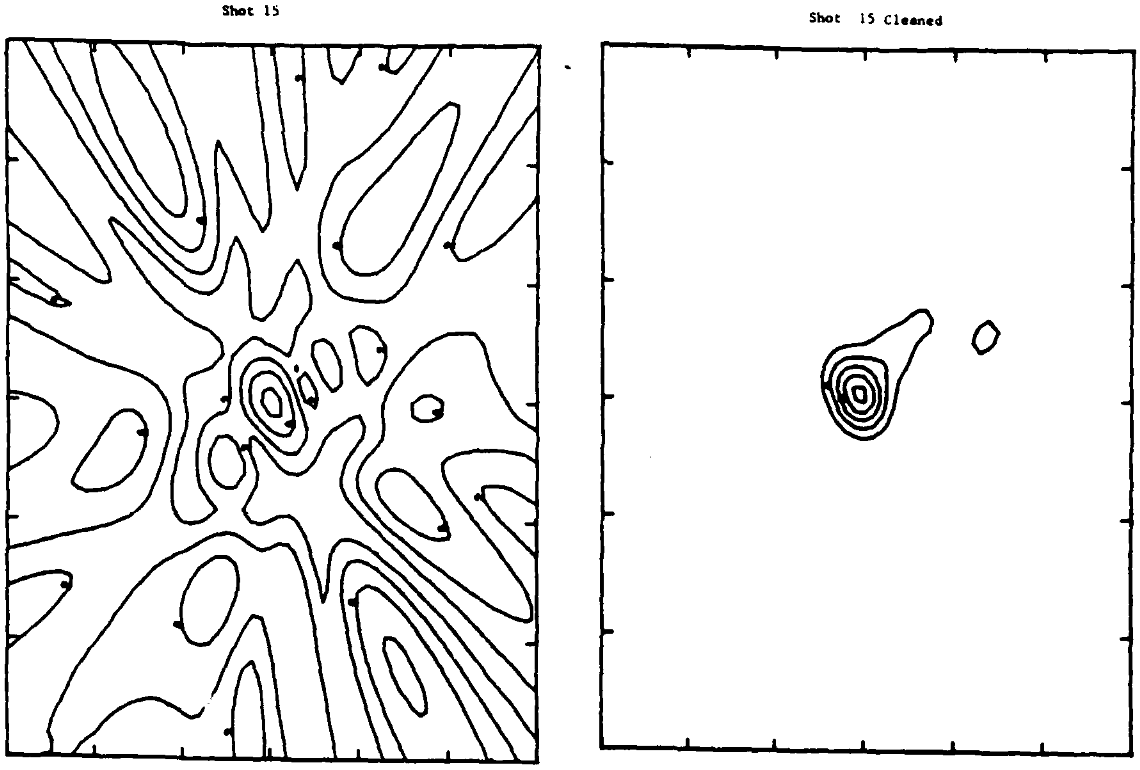

Figure 3 (Continued)—B, C, D, E, F, G—Holographic reconstructions (horizontal plane) for several "shots" during spring-summer 1986. 3B, C, D, represent shots 13, 14, and 15 of 5/13/86 during disturbed ionospheric conditions. CLEANed representations are also included. 3E, F, and G are shots 1, 2, and 3 taken at a later date under undisturbed conditions.

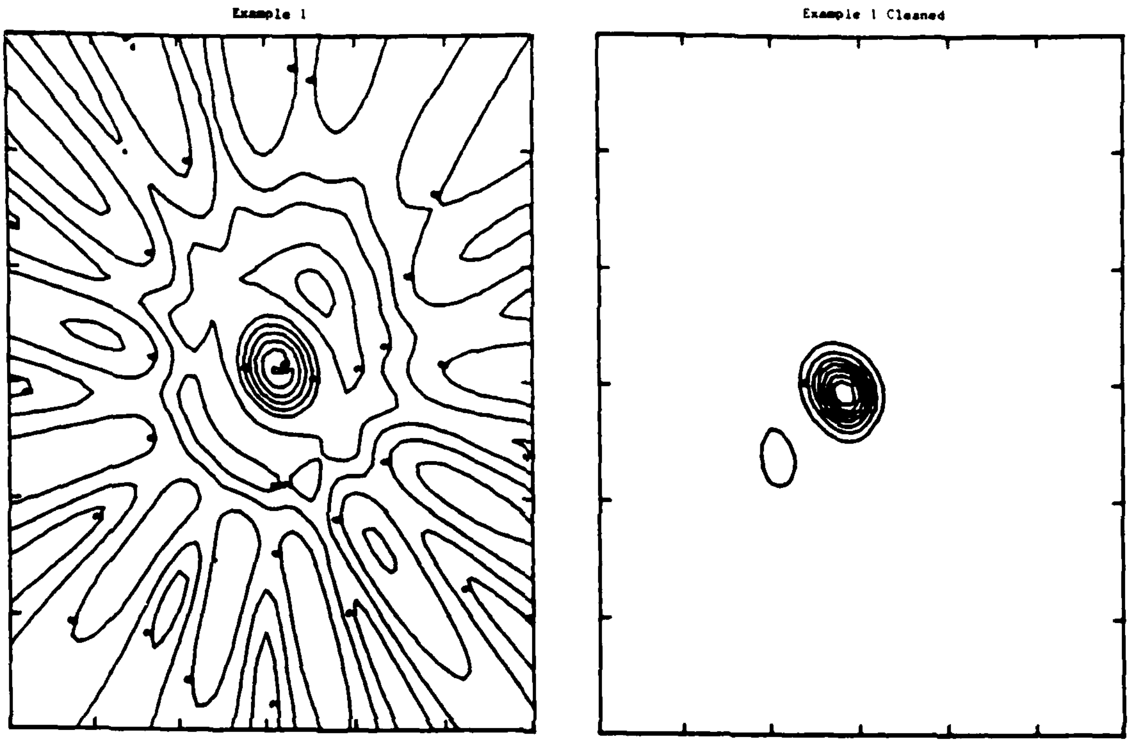

Figure 3 (Continued)—B, C, D, E, F, G—Holographic reconstructions (horizontal plane) for several "shots" during spring-summer 1986. 3B, C, D, represent shots 13, 14, and 15 of 5/13/86 during disturbed ionospheric conditions. CLEANed representations are also included. 3E, F, and G are shots 1, 2, and 3 taken at a later date under undisturbed conditions.

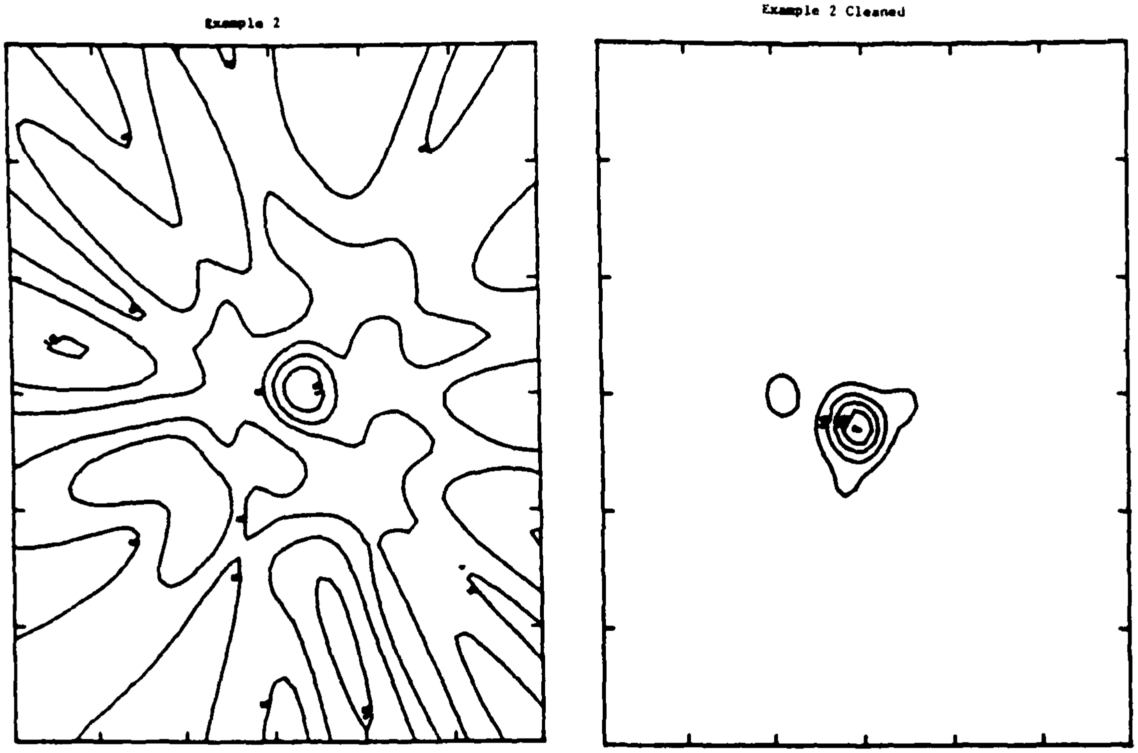

Figure 3 (Continued)—B, C, D, E, F, G—Holographic reconstructions (horizontal plane) for several "shots" during spring-summer 1986. 3B, C, D, represent shots 13, 14, and 15 of 5/13/86 during disturbed ionospheric conditions. CLEANed representations are also included. 3E, F, and G are shots 1, 2, and 3 taken at a later date under undisturbed conditions.

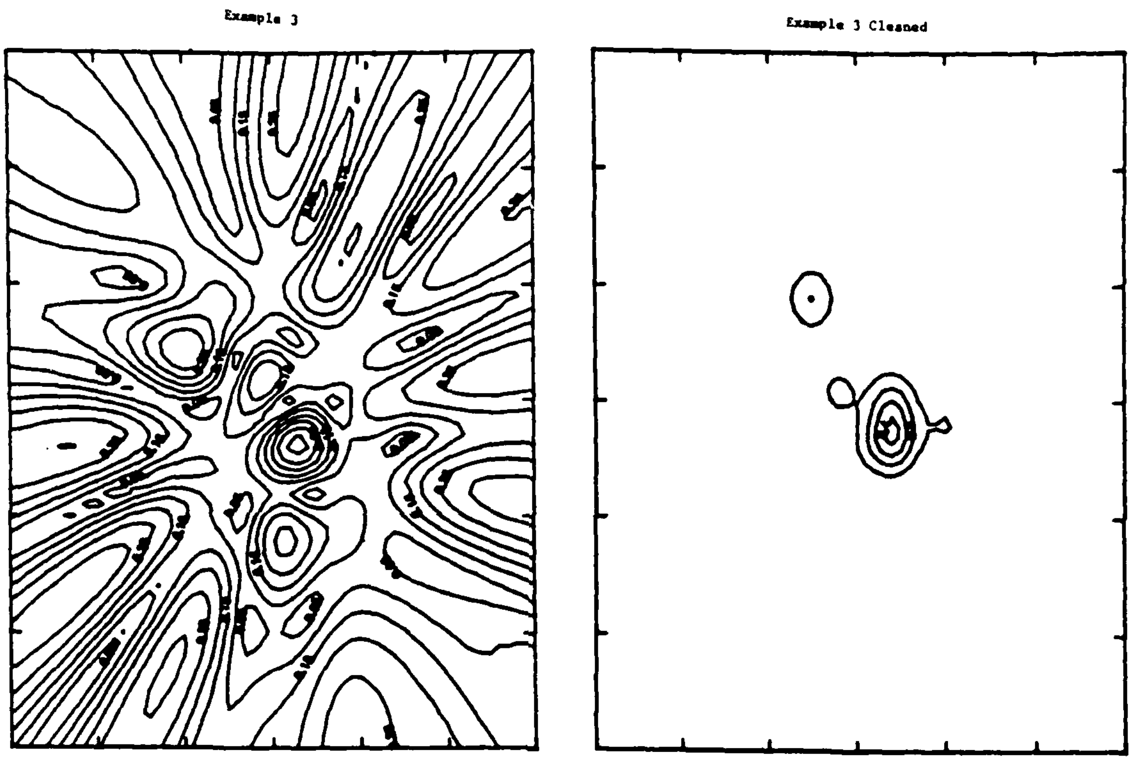

Figure 3 (Continued)—B, C, D, E, F, G—Holographic reconstructions (horizontal plane) for several "shots" during spring-summer 1986. 3B, C, D, represent shots 13, 14, and 15 of 5/13/86 during disturbed ionospheric conditions. CLEANed representations are also included. 3E, F, and G are shots 1, 2, and 3 taken at a later date under undisturbed conditions.

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